

Setting the stellar evolution clock for intermediate age populations

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Abstract. In this invited talk I show how the *reddest and rarest* galaxies at high redshift ($z \simeq 1.5$) can be used to set the stellar evolution clock. I argue that one can confidently compute the collapse redshift of these objects. This yields to a high collapse redshift ($z > 6$) and therefore their age is well constrained (in all cosmologies) between 3 and 4 Gyr. I also show that this is, indeed, the age derived using a variety of synthetic stellar population models when proper statistical tools are used to analyse their observed spectral energy distribution. This allows me to conclude that *all* stellar population models yield to the same consistent age for these galaxies, i.e. about 3.5 Gyr and that the stellar clock is properly set. Low ages are therefore excluded with high confidence.

1. Introduction

Traditionally, the stellar clock has been set on stellar objects at $z = 0$, namely the Sun. Here I describe how one can find passively evolving galaxies at high-redshift and use them to set the stellar clock of stellar populations of intermediate age.

The most problematic issue is how to find galaxies at high redshift. The study of ‘normal’ star-forming galaxies at $z > 2$ has developed into a booming astronomical industry over the past 4 years (e.g. Steidel et al. 1998). Since most high-redshift galaxies are optically selected, one is biased towards blue objects that show recent star formation, i.e. biased towards composite stellar populations with several episodes of star formation. In this way, one can only hope to determine the age of the *youngest* stars at high-redshift, not a very useful age indicator. Nevertheless, a few valiant efforts have been carried out in order to determine the age of the stellar populations in high-redshift galaxies (Chambers & Charlot 1990).

A more promising way to find passively evolving objects is utilizing radio galaxies. One of the cleanest results in extra-galactic astronomy is that all powerful ($P > 10^{24} \text{ WHz}^{-1}\text{sr}^{-1}$) radio sources in the present-day universe are hosted by giant ellipticals. It is then reasonable to assume that high-redshift radio sources also reside in ellipticals or their progenitors. By selecting radio galaxies at mJy flux levels we (Dunlop et al. 1996, Spinrad et al. 1997, Dunlop 1998, Dey et al. 1999) have shown that it is possible to find examples of well evolved galaxies at $z \sim 1.5$ whose near-ultraviolet spectrum is uncontaminated by a recent burst of star formation. Keck spectroscopy of these objects has

yielded the first detection of stellar absorption features from *old* stars at $z \leq 1.5$ and thus the first *reliable* age-dating of high-redshift objects. The best example in our sample is 53W069. Using WFC2 and NICMOS images below and above the 4000 Å break we have verified that the above also holds for its morphological properties and scalelengths (Dunlop 1998). Using a 2-dimensional fitting code it is possible to show that 53W069 is consistent with a $r^{1/4}$ law and inconsistent with an exponential disc profile. Furthermore, a physical half-light radius of $r_e \approx 4$ kpc has been obtained assuming $\Omega = 1$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which lies exactly in the Kormendy relation for ellipticals (Dunlop 1998).

The traditional approach would be to use synthetic stellar population models to derive the age of 53W069 from its observed spectral energy distribution. Here I argue, that it is possible to use observations of the abundances and clustering of high-redshift galaxies to estimate the power spectrum on small scales, and thus constrain the age of 53W069 without the need of stellar evolution physics knowledge. The following section summarizes the results of this exercise, as given by Peacock et al. (1998).

2. Small-scale power spectrum

2.1. Press-Schechter apparatus

The standard framework for interpreting the abundances of high-redshift objects in terms of structure-formation models, was outlined by Efstathiou & Rees (1988). The formalism of Press & Schechter (1974) gives a way of calculating the fraction F_c of the mass in the universe which has collapsed into objects more massive than some limit M :

$$F_c(> M, z) = 1 - \text{erf} \left[\frac{\delta_c}{\sqrt{2} \sigma(M)} \right]. \quad (1)$$

Here, $\sigma(M)$ is the rms fractional density contrast obtained by filtering the linear-theory density field on the required scale. In practice, this filtering is usually performed with a spherical ‘top hat’ filter of radius R , with a corresponding mass of $4\pi\rho_b R^3/3$, where ρ_b is the background density. The number δ_c is the linear-theory critical overdensity, which for a ‘top-hat’ overdensity undergoing spherical collapse is 1.686 – virtually independent of Ω . This form describes numerical simulations very well (see e.g. Ma & Bertschinger 1994). The main assumption is that the density field obeys Gaussian statistics, which is true in most inflationary models. Given some estimate of F_c , the number $\sigma(R)$ can then be inferred. Note that for rare objects this is a pleasingly robust process: a large error in F_c will give only a small error in $\sigma(R)$, because the abundance is exponentially sensitive to σ .

Total masses are of course ill-defined, and a better quantity to use is the velocity dispersion. Virial equilibrium for a halo of mass M and proper radius r demands a circular orbital velocity of $V_c^2 = \frac{GM}{r}$. For a spherically collapsed object this velocity can be converted directly into a Lagrangian comoving radius which contains the mass of the object within the virialization radius (e.g. White,

Efstathiou & Frenk 1993):

$$R/h^{-1} \text{ Mpc} = \frac{2^{1/2} [V_c/100 \text{ km s}^{-1}]}{\Omega_m^{1/2} (1+z_c)^{1/2} f_c^{1/6}}. \quad (2)$$

Here, z_c is the redshift of virialization; Ω_m is the *present* value of the matter density parameter; f_c is the density contrast at virialization of the newly-collapsed object relative to the background, which is adequately approximated by $f_c = 178/\Omega_m^{0.6}(z_c)$, with only a slight sensitivity to whether Λ is non-zero (Eke, Cole & Frenk 1996). For isothermal-sphere haloes, the velocity dispersion is $\sigma_v = V_c/\sqrt{2}$. Given a formation redshift of interest, and a velocity dispersion, there is then a direct route to the Lagrangian radius from which the proto-object collapsed.

2.2. Abundances and masses of high-redshift objects

Three classes of high-redshift object can be used to set constraints on the small-scale power spectrum at high redshift:

(1) Damped Lyman- α absorbers

If the fraction of baryons in the virialized dark matter halos equals the global value Ω_{BB} , then data on these systems can be used to infer the total fraction of matter that has collapsed into bound structures at high redshifts (see Peacock et al 1998 and refs. therein). Therefore,

$$F_c = \frac{\Omega_{bHI}}{\Omega_{BB}} \simeq 0.12h \quad (3)$$

for these systems. In this case alone, an explicit value of h is required in order to obtain the collapsed fraction; $h = 0.65$ is assumed and we have adopted $\Omega_{BB}h^2 = 0.02$.

(2) Lyman-limit galaxies

Steidel et al. (1996) identified star-forming galaxies between $z = 3$ and 3.5 by looking for objects with a spectral break redwards of the U band. Steidel et al. give the comoving density of their galaxies as

$$N(\Omega = 1) \simeq 10^{-2.54} (h^{-1} \text{ Mpc})^{-3}. \quad (4)$$

Direct dynamical determinations of these masses are still lacking in most cases. Steidel et al. attempt to infer a velocity width by looking at the equivalent width of the C and Si absorption lines. These are saturated lines, and so the equivalent width is sensitive to the velocity dispersion; values in the range

$$\sigma_v \simeq 180 - 320 \text{ km s}^{-1} \quad (5)$$

are implied. In practice, this uncertainty in the velocity does not produce an important uncertainty in the conclusions.

(3) Red radio galaxies

This is the set of observations for which we wish to determine their collapse redshift. Two extremely red galaxies were found at $z = 1.43$ and 1.55, over an

area 1.68×10^{-3} sr, so a minimal comoving density is from one galaxy in this redshift range:

$$N(\Omega = 1)10^{-5.87} (h^{-1} \text{ Mpc})^{-3}. \quad (6)$$

This figure is comparable to the density of the richest Abell clusters, and is thus in reasonable agreement with the discovery that rich high-redshift clusters appear to contain radio-quiet examples of similarly red galaxies (Dickinson 1995).

Since the velocity dispersions of these galaxies are not observed, they must be inferred indirectly. This is possible because of the known present-day Faber-Jackson relation for ellipticals. Their large-aperture absolute magnitude is $M_V(z = 1.55 | \Omega = 1) \simeq -21.62 - 5 \log_{10} h$ (measured direct in the rest frame). This yields to $\sigma_v = 222$ to 292 km s^{-1} , which is a very reasonable range for a giant elliptical, and is adopted in the following analysis.

Having established an abundance and an equivalent circular velocity for these galaxies, the treatment of them will differ in one critical way from the Lyman- α and Lyman-limit galaxies. For these, the normal Press-Schechter approach assumes the systems under study to be newly born. For the Lyman- α and Lyman-limit galaxies, this may not be a bad approximation, since they are evolving rapidly and/or display high levels of star-formation activity. For the radio galaxies, conversely, their inactivity suggests that they may have existed as discrete systems at redshifts much higher than $z \simeq 1.5$. The strategy will therefore be to apply the Press-Schechter machinery at some unknown formation redshift, and see what range of redshift gives a consistent degree of inhomogeneity.

2.3. Collapse redshifts and ages for red radio galaxies

Fig. 1 shows the $\sigma(R)$ data which result from the Press-Schechter analysis, for three cosmologies. The $\sigma(R)$ numbers measured at various high redshifts have been translated to $z = 0$ using the appropriate linear growth law for density perturbations.

The open symbols give the results for the Lyman-limit (largest R) and Lyman- α (smallest R) systems. The approximately horizontal error bars show the effect of the quoted range of velocity dispersions for a fixed abundance; the vertical errors show the effect of changing the abundance by a factor 2 at fixed velocity dispersion. The locus implied by the red radio galaxies sits in between. The different points show the effects of varying collapse redshift: $z_c = 2, 4, \dots, 12$ [lowest redshift gives lowest $\sigma(R)$]. Clearly, collapse redshifts of 6 – 8 are favoured for consistency with the other data on high-redshift galaxies, *independent of theoretical preconceptions and independent of the age of these galaxies* (see also Kashlinsky & Jimenez (1997)).

What is then the age of the red radio galaxies as inferred by their high collapse redshifts? First bear in mind that in a hierarchy some of the stars in a galaxy will inevitably form in sub-units before the epoch of collapse. At the time of final collapse, the typical stellar age will be some fraction α of the age of the universe at that time: $\text{age} = t(z_{\text{obs}}) - t(z_c) + \alpha t(z_c)$. We can rule out $\alpha = 1$ (i.e. all stars forming in small subunits just after the big bang). For present-day ellipticals, the tight colour-magnitude relation only allows an approximate doubling of the mass through mergers since the termination of star formation (Bower et al. 1992). This corresponds to $\alpha \simeq 0.3$ (Peacock 1991). A non-zero α

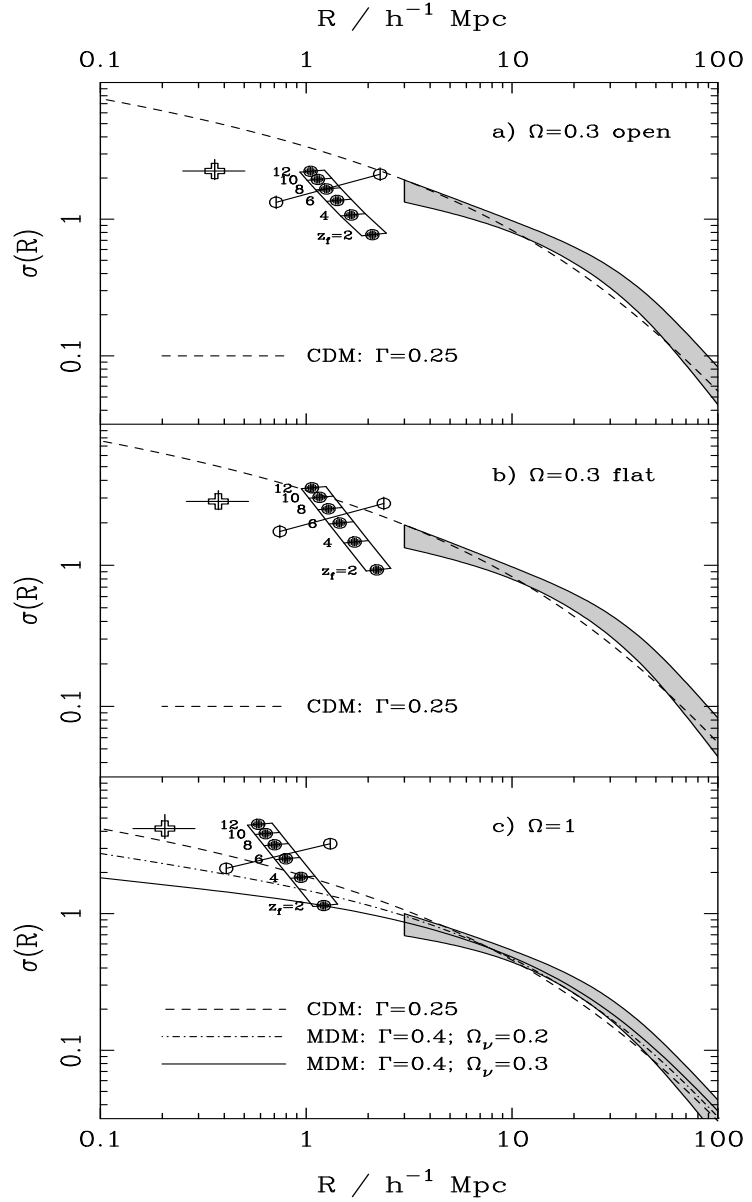


Figure 1. The present-day linear fractional rms fluctuation in density averaged in spheres of radius R . The data points are Lyman- α galaxies (open cross) and Lyman-limit galaxies (open circles). The diagonal band with solid points shows red radio galaxies with assumed collapse redshifts 2, 4, \dots 12. The vertical error bars show the effect of a change in abundance by a factor 2. The horizontal errors correspond to different choices for the circular velocities of the dark-matter haloes that host the galaxies. The shaded region at large R gives the results inferred from galaxy clustering. The lines show CDM and MDM predictions, with a large-scale normalization of $\sigma_8 = 0.55$ for $\Omega = 1$ or $\sigma_8 = 1$ for the low-density models.

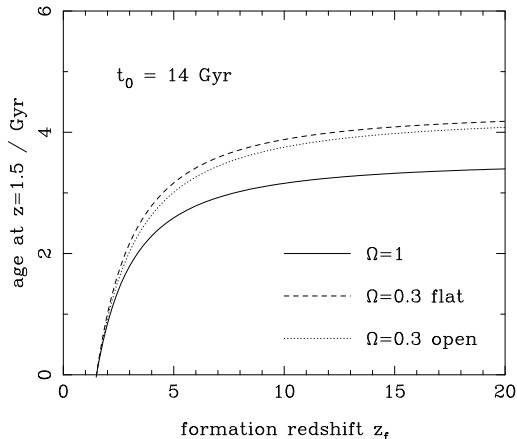


Figure 2. Age of the Universe at $z = 1.5$ for several cosmologies, it transpires from the figure that the age of galaxies formed at $z > 5$ is well constrained between 3 and 4 Gyr

just corresponds to scaling the collapse redshift as apparent $(1+z_c) \propto (1-\alpha)^{-2/3}$, since $t \propto (1+z)^{-3/2}$ at high redshifts for all cosmologies. For example, a galaxy which collapsed at $z = 6$ would have an apparent age corresponding to a collapse redshift of 7.9 for $\alpha = 0.3$.

Converting the ages for the galaxies to an apparent collapse redshift depends on the cosmological model, but particularly on H_0 . Some of this uncertainty may be circumvented by fixing the age of the universe. After all, it is of no interest to ask about formation redshifts in a model with e.g. $\Omega = 1$, $h = 0.7$ when the whole universe then has an age of only 9.5 Gyr. If $\Omega = 1$ is to be tenable then either $h < 0.5$ against all the evidence or there must be an error in the stellar evolution timescale. If the stellar timescales are wrong by a fixed factor, then these two possibilities are degenerate. It therefore makes sense to measure galaxy ages only in units of the age of the universe – or, equivalently, to choose freely an apparent Hubble constant which gives the universe an age comparable to that inferred for globular clusters. In this spirit, Fig. 2 gives apparent ages as a function of effective collapse redshift for models in which the age of the universe is forced to be 14 Gyr (e.g. Jimenez et al. 1996, see also Fusi-Peccì in this volume).

This plot shows that *the ages of the red radio galaxies are not permitted very much freedom*. Formation redshifts in the range 6 to 8 predict an age of close to 3.1 Gyr for $\Omega = 1$, or 3.7 Gyr for low-density models, irrespective of whether Λ is nonzero. The age- z_c relation is rather flat, and this gives a robust estimate of age once we have some idea of z_c through the abundance arguments.

3. The age of 53w069

As seen from the previous section, galaxies at $z \sim 1.5$ with low comoving densities, are excellent sites for setting the stellar clock since their age is known

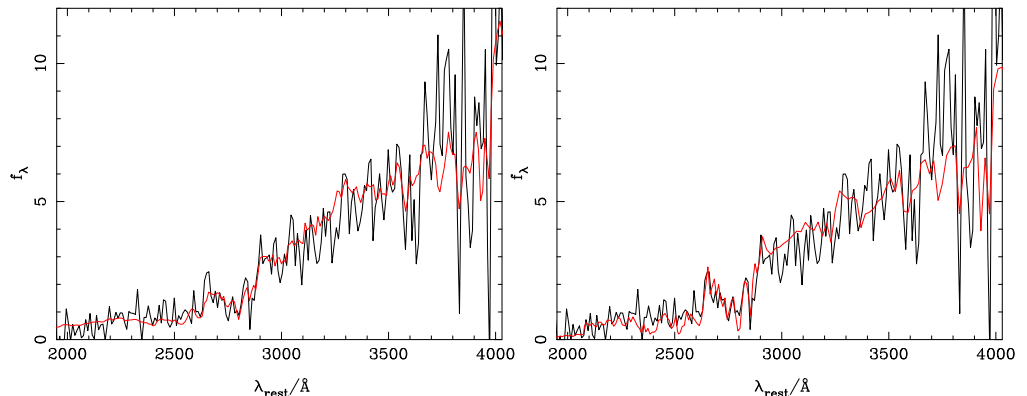


Figure 3. Left panel: the spectrum of 53W069 overlaid with the best fitting Bruzual-Charlot model, which has an age of 3.3 Gyr. Right panel: Same as before but now overlaid with the best fitting model from Jimenez et al. (1999b), which has an age of 4.0 Gyr.

from other independent arguments. In what remains I will analyse how some of the different set of synthetic stellar population models available perform when trying to recover the age of 53W069 (the reddest passively evolving galaxy found at high- z).

The spectral energy distribution (SED) of 53W069 is presented in Fig. 3. In order to determine its age I have performed properly weighted chi-squared fits to the ultra-violet SED using the popular Worthey and also Bruzual & Charlot synthetic stellar population models and the models developed by our group (Jimenez et al. 1999b). The results are listed in Table 1. A few important points transpire from this table. First, all models yield ages larger than 3 Gyr for 53W069. Second, column 1 and 2 show that some models seem to be internally inconsistent, in the sense that they are capable of reproducing very red $R - K$ colours at a much younger age than they can reproduce the ultraviolet SED or the spectral breaks. However, since $R - K$ is mainly affected by the evolution of the late stages of stellar evolution, one should focus on ages derived from the UV-spectrum since this only depends on the correct prediction of the MSTO, a simpler and thus an easier part to model. Indeed, not do so it tantamount to throwing away the new, more robust information which can be gleaned from the spectroscopy. If one focuses on the results of 53W069 then, ignoring the anomalously young $R - K$ age produced by some models, all sets are basically in good agreement that the overall shape of the UV SED is consistent with an age in the range 3.0 to 4.0 Gyr, and certainly yielding a robust (99% confidence) minimum age of 3.0 Gyr. Thus one finds that *all* models yield basically to the same result, in perfect agreement with the independently derived age in section 2. Therefore, one can conclude that the stellar clock is properly set, even at these young ages. The anomalously small ages (about 1 Gyr) obtained by fitting the $R - K$ colours, can be entirely attributed to the fact that K (rest-frame 1μ) is

entirely dominated by the giants population, and thus by mass loss and other complications from stellar evolution during its late stages.

Spectroscopically, 53W069 thus appears to be the best known example of old, passively-evolving elliptical galaxies at redshifts as high as $z \sim 1.5$. It is worth noting that $z \sim 1.5$ is the redshift where one expects galaxies to be redder, and not at higher redshift (see Jimenez et al. 1999a)

Table 1. A comparison of age estimates for the stellar population of 53W069 as derived from the instantaneous burst models of Bruzual & Charlot (B&C), Worthey (1998) (W) and Jimenez et al (1999b) (J99), when used to fit different spectral indicators of age.

Feature	B&C	W98	J99
UV-SED	3.3 Gyr	3.1 Gyr	3.7 Gyr
$R - K$	1.6 Gyr	2.0 Gyr	4.0 Gyr
2649 Å	5.0 Gyr	4.0 Gyr	4.0 Gyr
2900 Å	4.5 Gyr	4.2 Gyr	4.0 Gyr

In summary, the new data on 53W069 clearly show that the Universe at $z \sim 1.5$ contains stellar systems whose populations are 3 to 4 Gyr old. At $z \sim 1.5$ the Universe was less than 30% of its present age, and the uncertainties are largely independent of those encountered in GCs studies. The existence of 53W069 permits only low Hubble constants and/or low cosmic densities; in particular, an $\Omega = 1$ Universe requires $H_0 \leq 45 \text{ km s}^{-1} \text{ Mpc}^{-1}$. On the other hand, in an Universe with a cosmological constant, 53W069 requires $\Omega_\lambda \geq 0.4$ if $H_0 \geq 60 \text{ km s}^{-1} \text{ Mpc}^{-1}$

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